中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

ATLAS HGTD探测器进展和 LGAD技术在未来电子对撞机的应用

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ATLAS EXPERIMENT

主要内容

1. ATLAS HGTD 探测器进展

2. LGAD 技术在对撞机实验的应用

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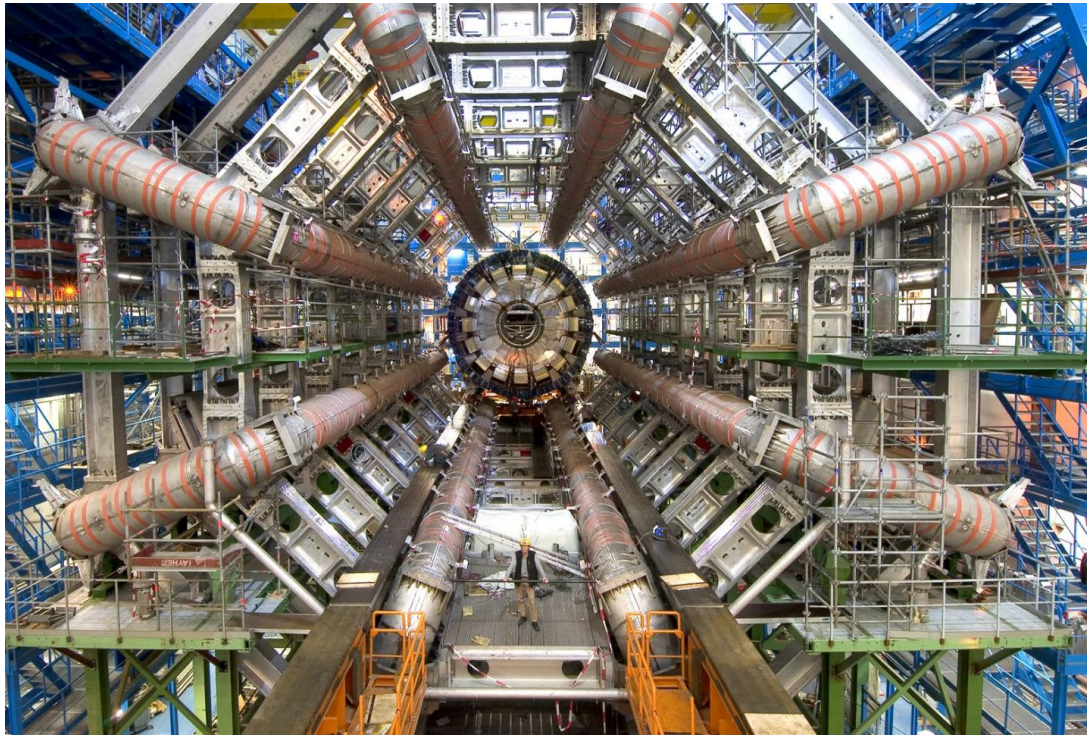
1. ATLAS HGTD 大型强子对撞机LHC与ATLAS实验



大型强子对撞机LHC

- 周长27km，总投资40亿美元
- 世界能量最高的加速器
- 质心系能14TeV（$14x10^{12}eV$）
- 位于瑞士与法国边境

ATLAS探测器

- 大约3000人的一个实验组
- 6层楼高（25米）的大型探测器
- 探测对撞产生粒子能量与动量

2029年升级为高亮度LHC （HL-LHC） ⟶ 事例堆积、强辐照环境

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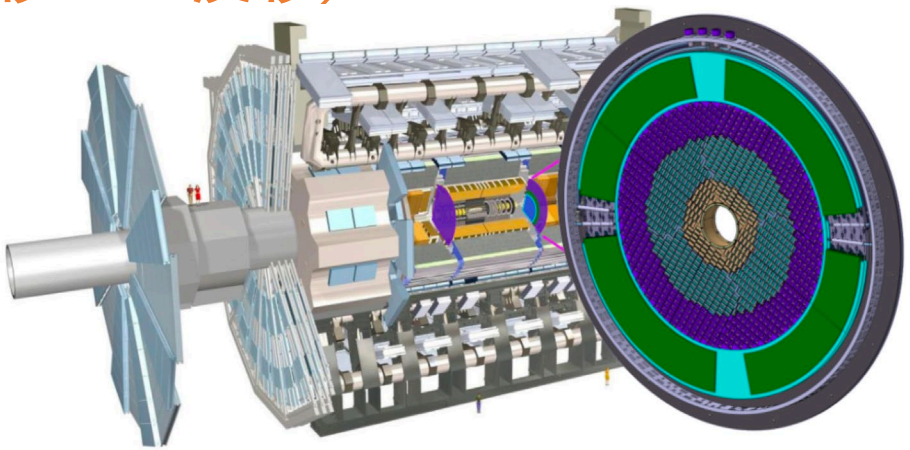
High Granularity Timing Detector (HGTD)
高颗粒度时间探测器

- 把粒子到达时间的测量精度提高2个数量级（数纳秒→30皮秒）
- 解决高亮度LHC对撞事例堆积问题
  - LGAD (Low-Gain Avalanche Diode)
  - 6.4平方米的硅探测器， 30皮秒的时间分辨
  - 毫米级的颗粒度，超过3.6M读出通道
  - 能承受2.5×10^{15} n_{eq}/cm^2的等效中子通量的辐照

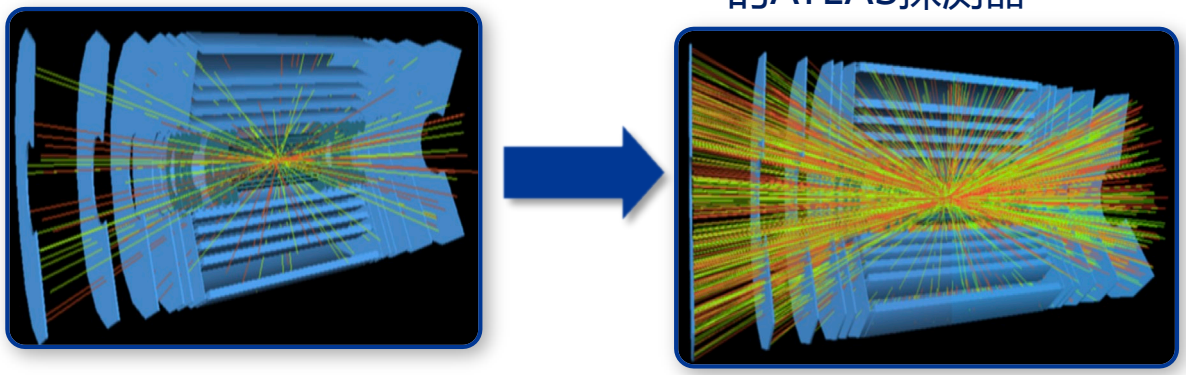
ATLAS探测器



- 中国组主导ATLAS HGTD探测器研制
  - 45%探测器组装 （34% 高能所，11%科大）
  - 100%抗辐照高时间分辨LGAD传感器
    （90% 高能所-微电子所，10%科大-微电子所）
  - 100%前端电子学（高能所，南大），
  - 50% ASIC测试，>16% 高压电子系统

目前的ATLAS探测器

高亮度LHC升级后的ATLAS探测器



面临问题：事例堆积、强辐照环境

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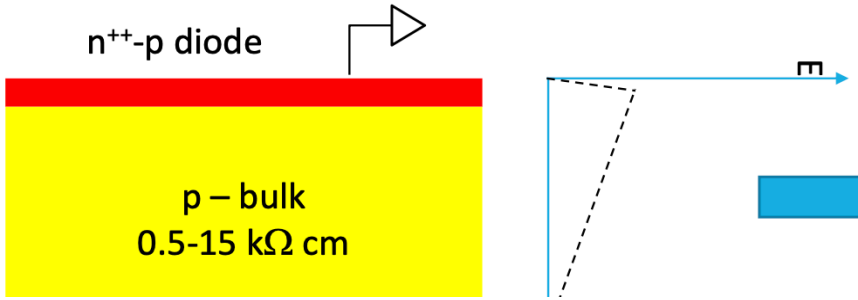
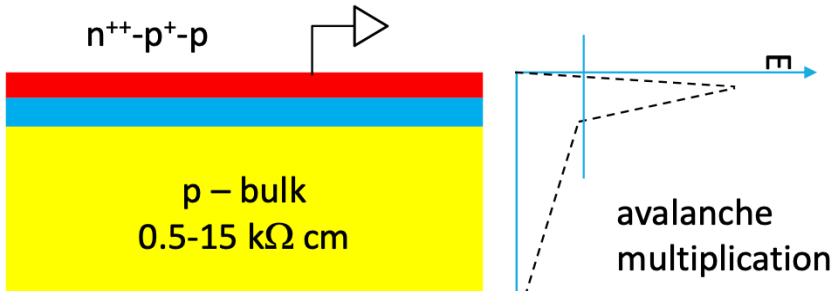
LGAD 时间性能提升

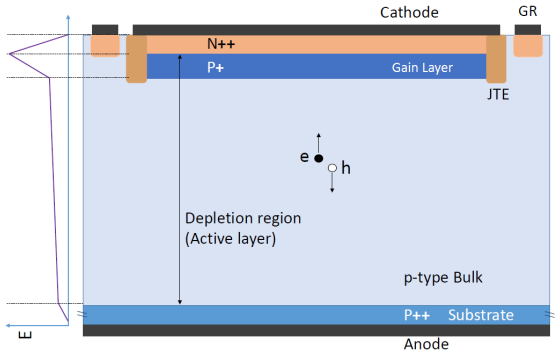
Conventional PIN diode



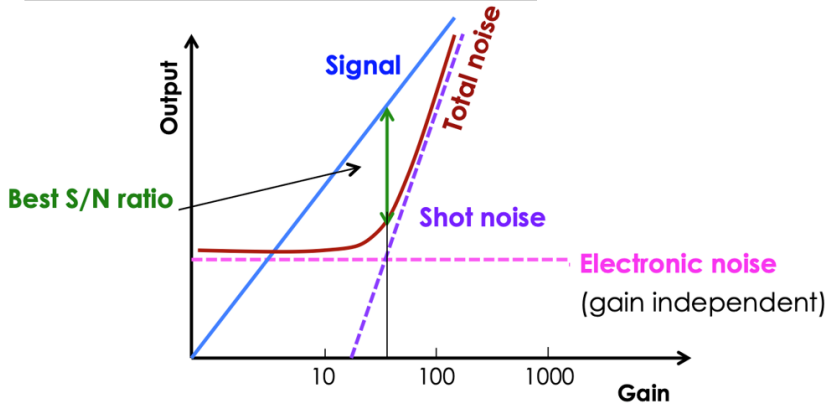
Low Gain Avalanche Diode
LGAD: P+ gain layer on top of PIN diode



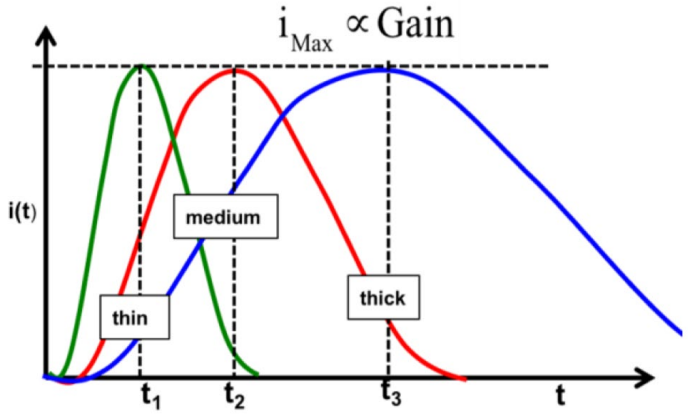
LGAD结构



- **Modest gain (10-50)**
  - Modest gain to increase S/N
  - High S/N, no self-triggering
- **Thin active layer**
  - Reduce Landau contribution caused by ionization
  - High drift velocity and decrease t_{rise}



$$\sigma_{\text{Jitter}} = \frac{N}{\mathrm{d}V/\mathrm{d}t} \approx t_{\text{rise}} / \left(\frac{S}{N}\right)$$



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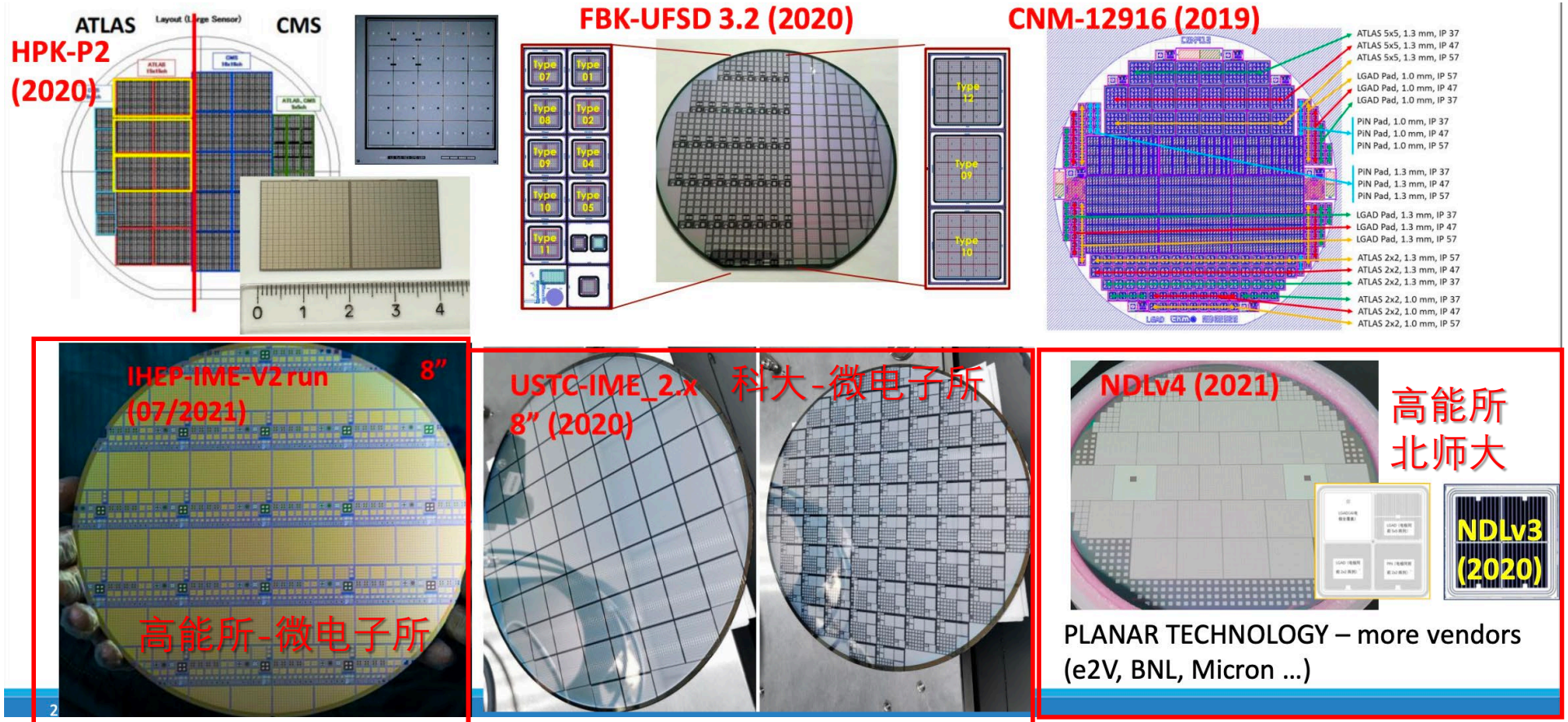
国内外形势

- 近年来，全世界范围涌现出很多研制LGAD硅传感器的单位
  - 国内：IHEP-IME (高能所-微电子所), USTC-IME (科大-微电子所), IHEP-NDL(高能所-北师大)
  - 国际：滨松HPK (Japan)，FBK (意大利)，CNM (西班牙）…
  - 高能所和科大分别独立设计传感器版图和工艺，在微电子所8寸晶圆工艺流片



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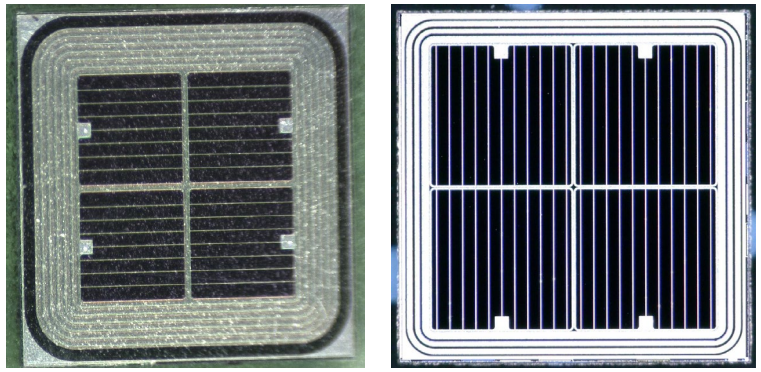
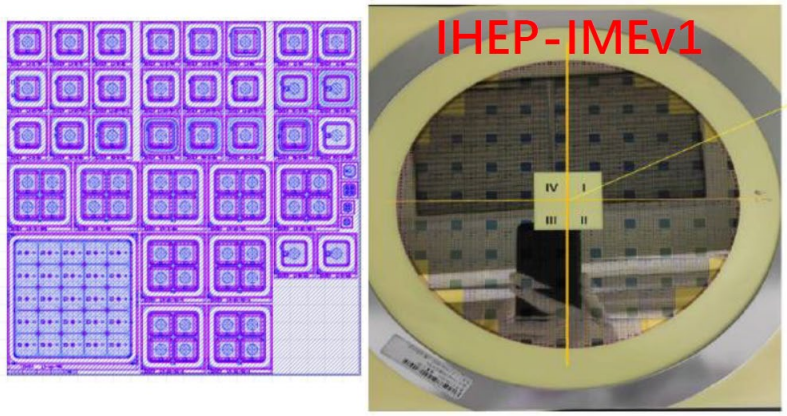
IHEP LGAD 研发时间线

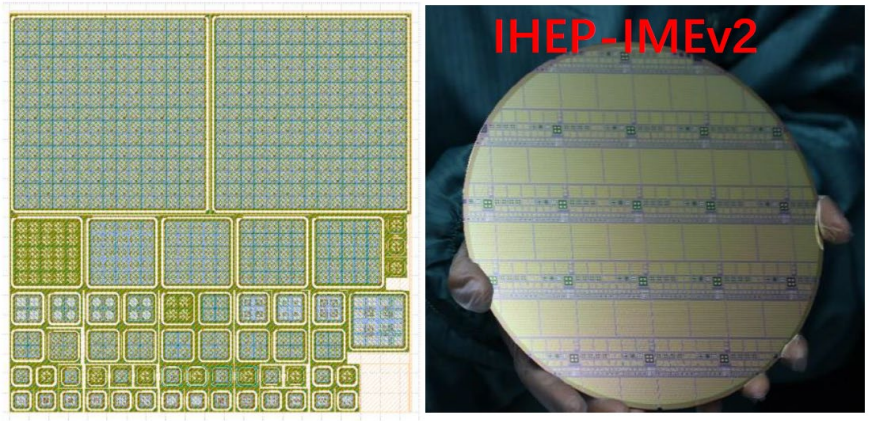
IHEP-NDL (2019)



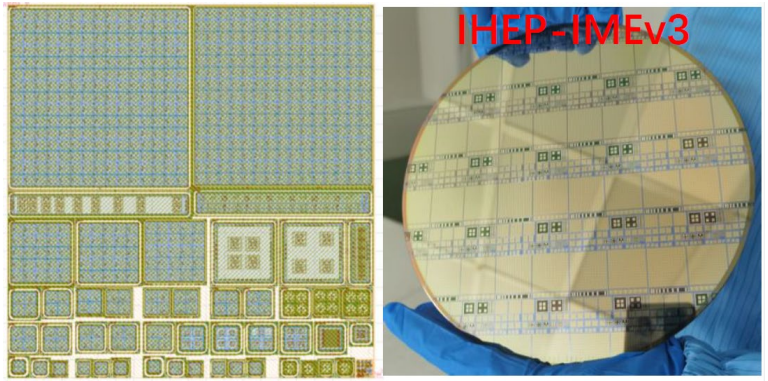
IHEP-IMEv1 (2020.9)



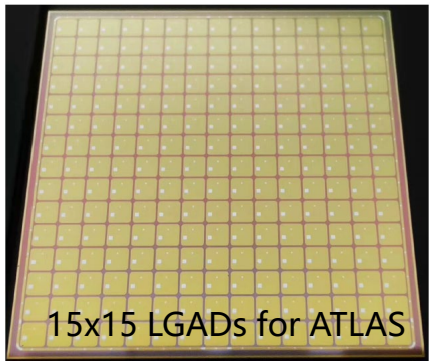
IHEP-IMEv2 (2021.6)

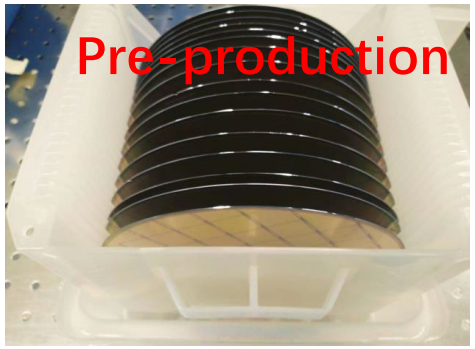


IHEP-IMEv3 (2022.5)



Pre-production for ATLAS (2023.7)





→ Mass production (2024.7)

欧洲核子中心（CERN）首次采购中国产的半导体器件，打破日本滨松垄断

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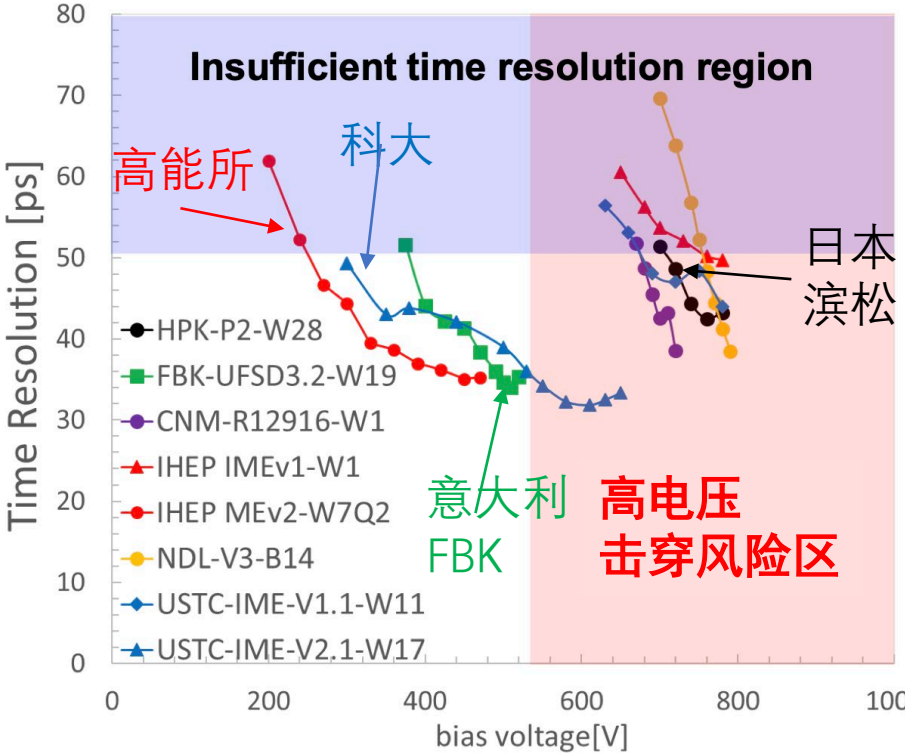
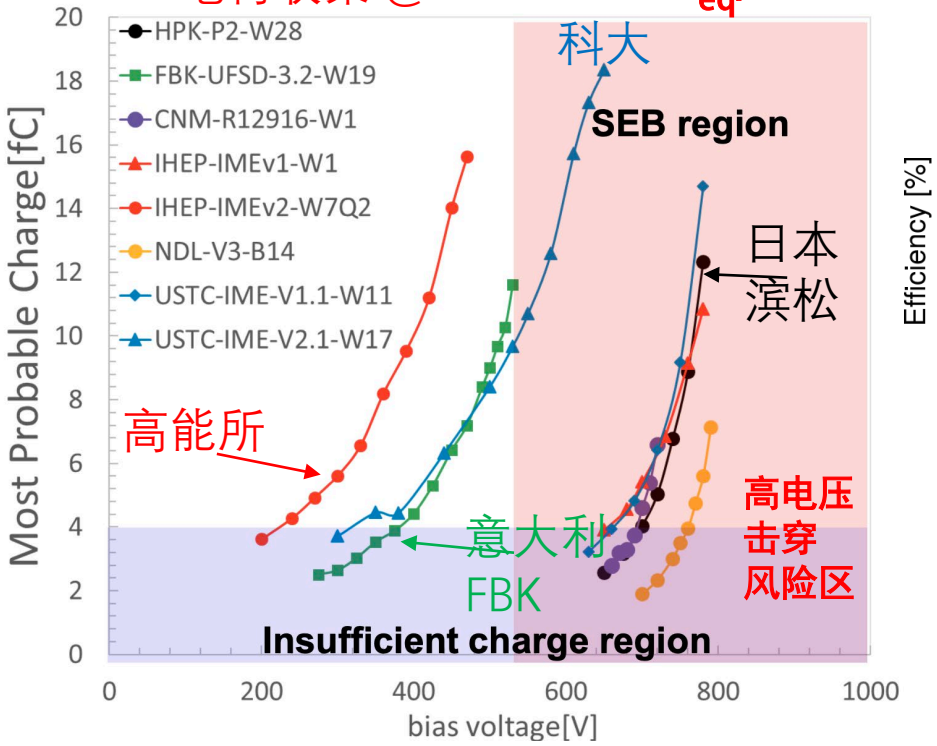
LGAD 抗辐照性能

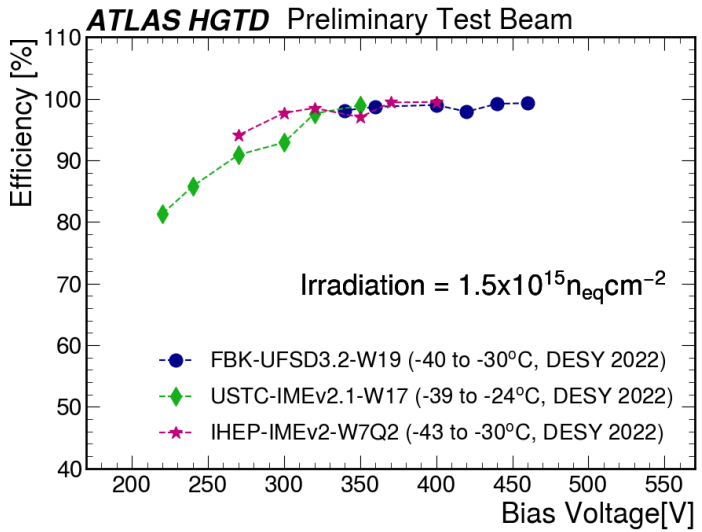
时间分辨率 @ 2.5×10^{15} n_{eq}/cm^2



电荷收集 @ 2.5×10^{15} n_{eq}/cm^2



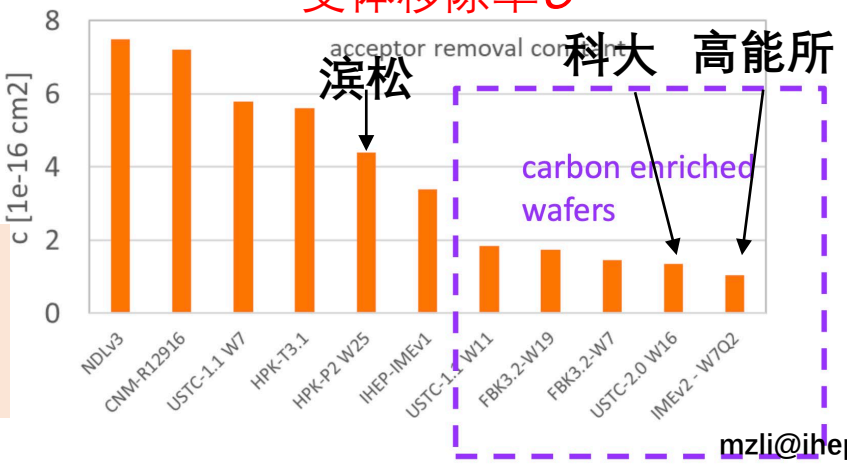
探测器效率>99%
@ 2.5×10^{15} n_{eq}/cm^2



辐照后，部分硼掺杂失活，增益下降(受体移除)
高能所、科大等设计掺碳工艺增强LGAD抗辐照性能

- 显著减低辐照后损伤（减低硼移除率）
- 抗辐照性能显著提高
- 目前抗辐照性能优于滨松

受体移除率C



高能所、科大研发的LGAD传感器
目前移除率最低 1-2 $\times10^{-16}cm^2$
（最佳抗辐照性能）

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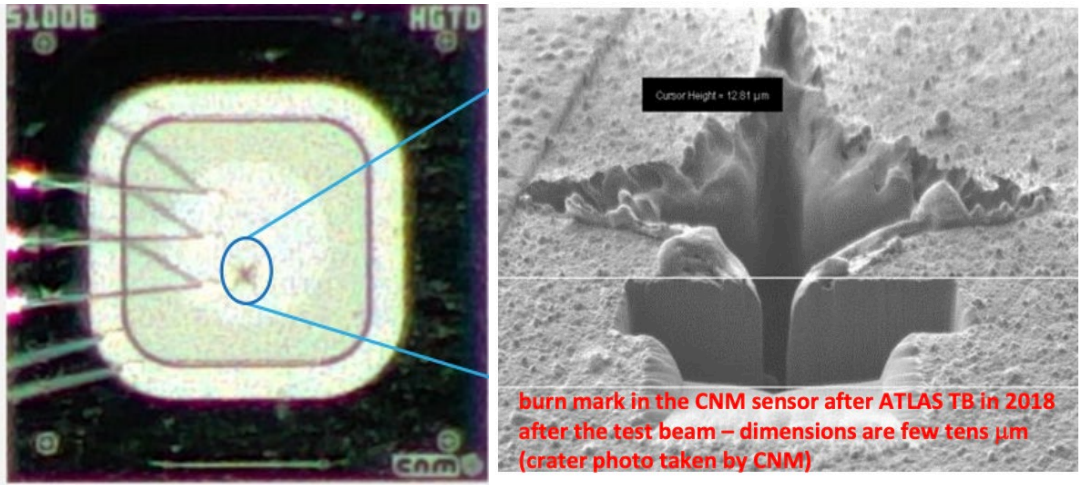
LGAD 抗辐照性能

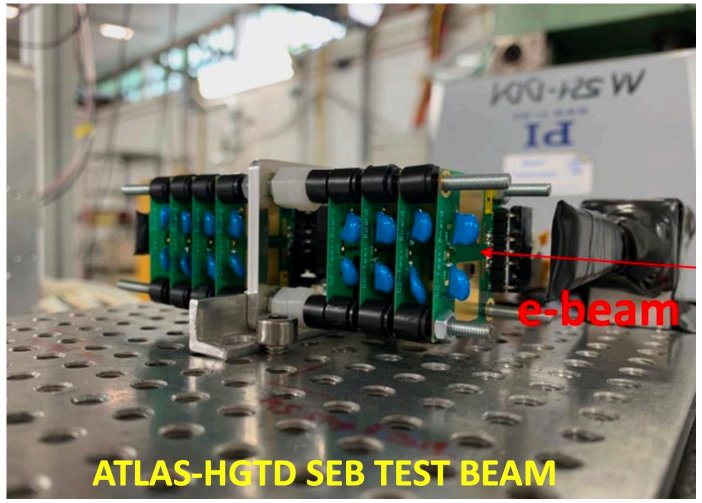
硅传感器的单粒子烧毁风险 Single Event Burnout (SEB)

- RD50, CMS and ATLAS 合作组在2021年确认LGAD的单粒子烧毁风险
- 高电压与高电场导致烧毁，辐照后工作电压要控制到< 550 V（50微米的硅传感器）
- ATLAS合作组开展欧洲核子中心（CERN）的高能质子流测试
  - 辐照后，不掺碳的LGAD（滨松，西班牙CNM）烧毁率较高
  - 掺碳的LGAD基本能通过测试（高能所，中科大，意大利FBK）
  - 高能所传感器辐照后，8个样品全部通过测试，无一烧毁

单粒子烧毁后LGAD（滨松/CNM）



CERN test beam: 120 GeV 质子束流



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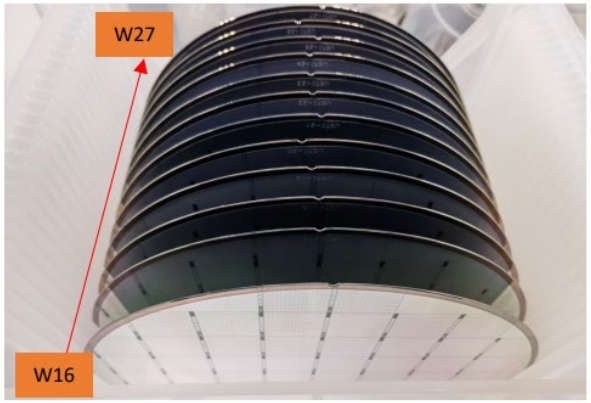
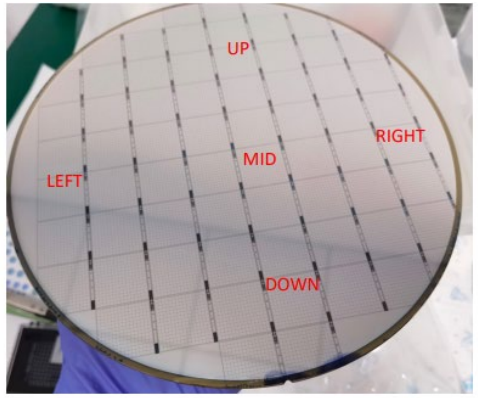
LGAD 探测器量产情况

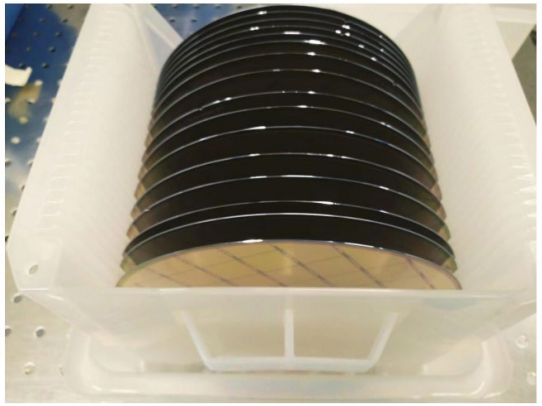
- 2023年高能所-微电子所赢得CERN的LGAD全额招标订单（>1.5万个LGAD）
  - 在日本滨松、意大利FBK等竞争下，高能所-微电子所赢下CERN招标
  - 欧洲核子中心（CERN）首次采购中国产的硅传感器
  - 象征着国产硅传感器国际地位显著提升
- 各单位在该项目LGAD传感器的贡献比重
  - 高能所-微电子所： 90%（66% CERN采购+ 24%实物贡献）
  - 中科大-微电子所：10% 实物贡献

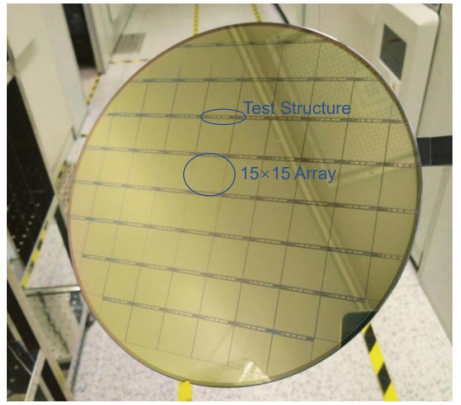
中科大-微电子所LGAD预生产





高能所-微电子所LGAD预生产





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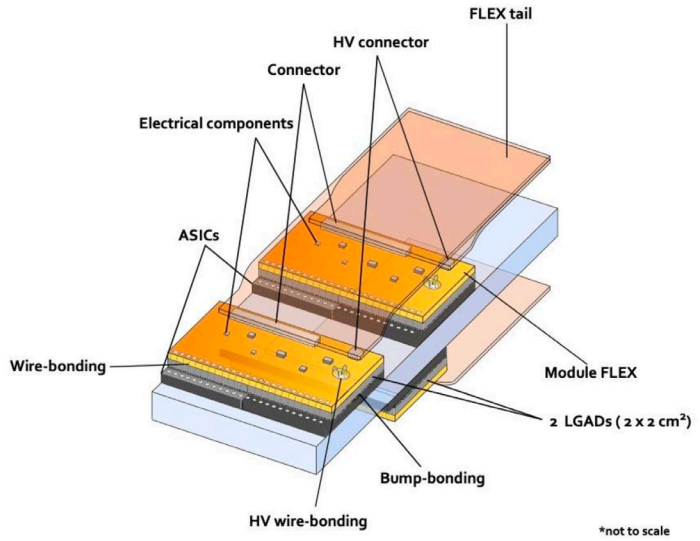
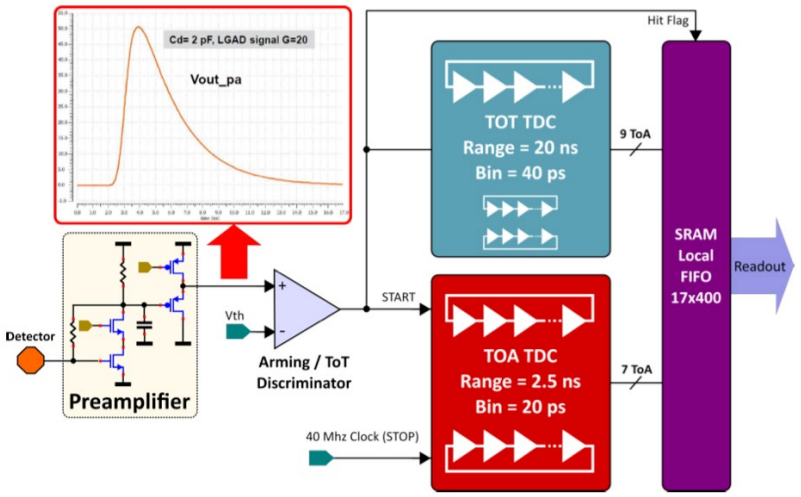
HGTD 探测器模块

- 一个HGTD模块包含两个 hybrid和一个 Flexible -PCB
  - Hybrid：15×15 LGAD + 15×15 ALTIROC ASIC

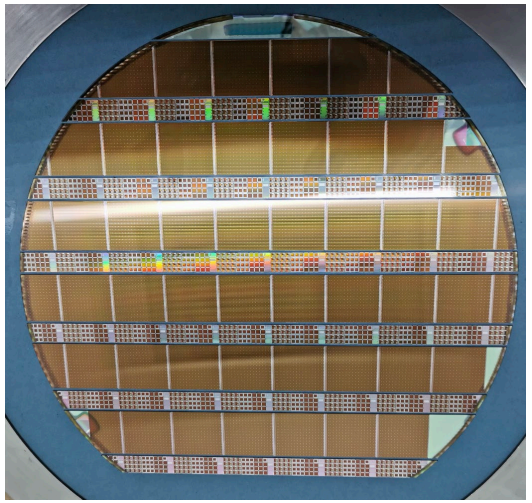
- 每个ALTIROC 有225 前端通道, 每个通道有：
  - 前置放大器 + 甄别器+TDC*2
  - 两个TDC (Time to Digital Converter) 提供信号定时数据
    - Time of Arrival (TOA) : Range of 2.5 ns and a bin of 20 ps (7 bits)
    - Time Over Threshold (TOT) : range of 20 ns and a bin of 40 ps (9 bits)



HGTD模块结构



ALTIROC 单通道设计



ALTIROC 晶元

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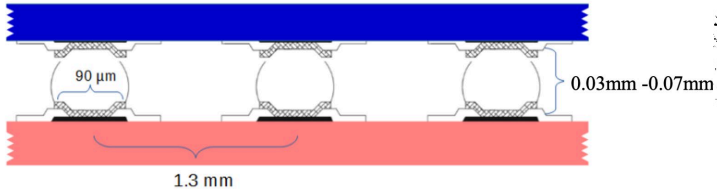
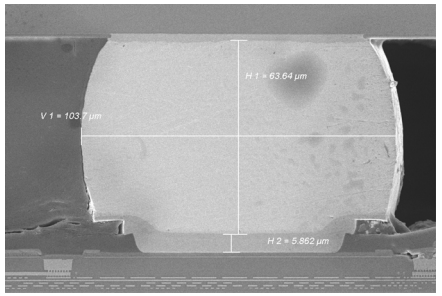
HGTD 探测器模块

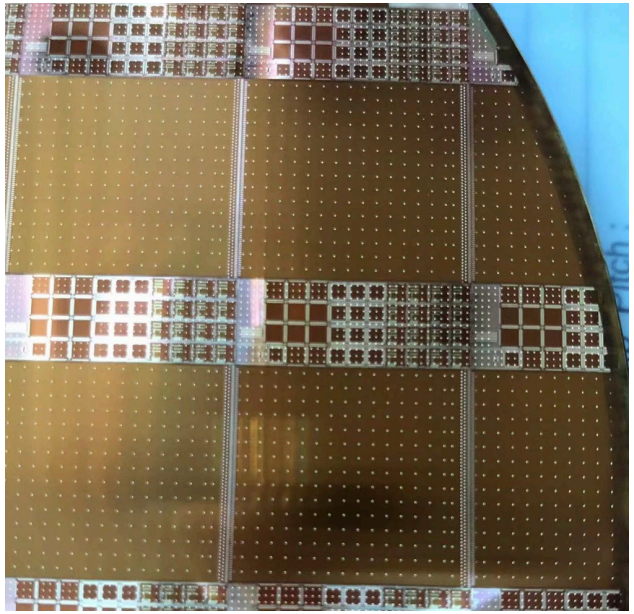


探测器模块：倒装焊封装

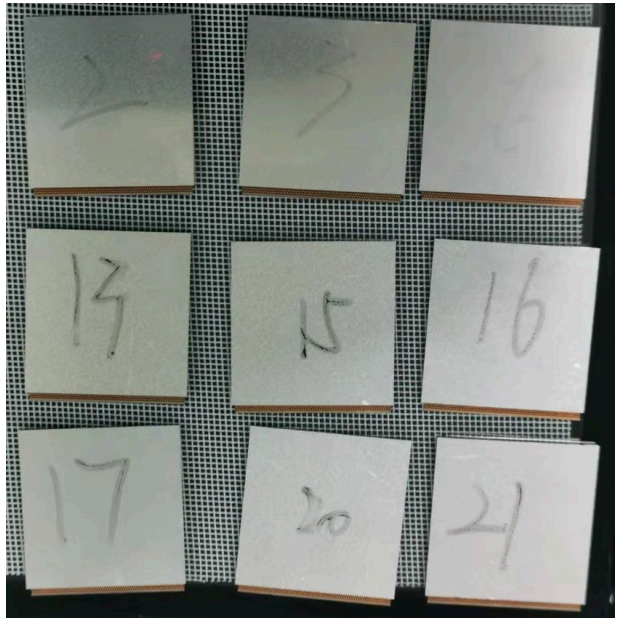
- 高能所承担项目中50%的倒装焊封装任务
- 高能所在国内已经研制出100+倒装焊模块
  - ALTIROC读出芯片 + 高能所-微电子所 LGAD



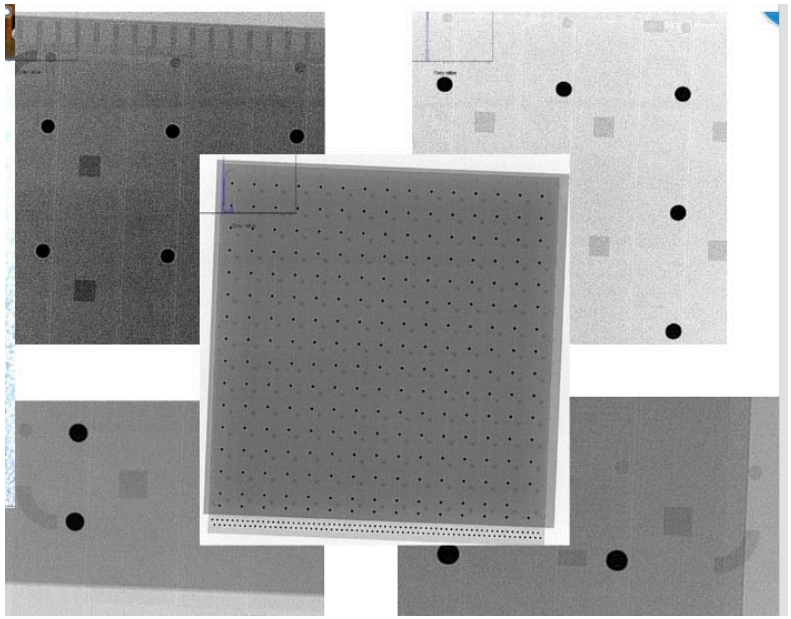
ALTIROC2 芯片晶圆植球



倒装焊模块后的模块



X-ray image of full-size hybrid



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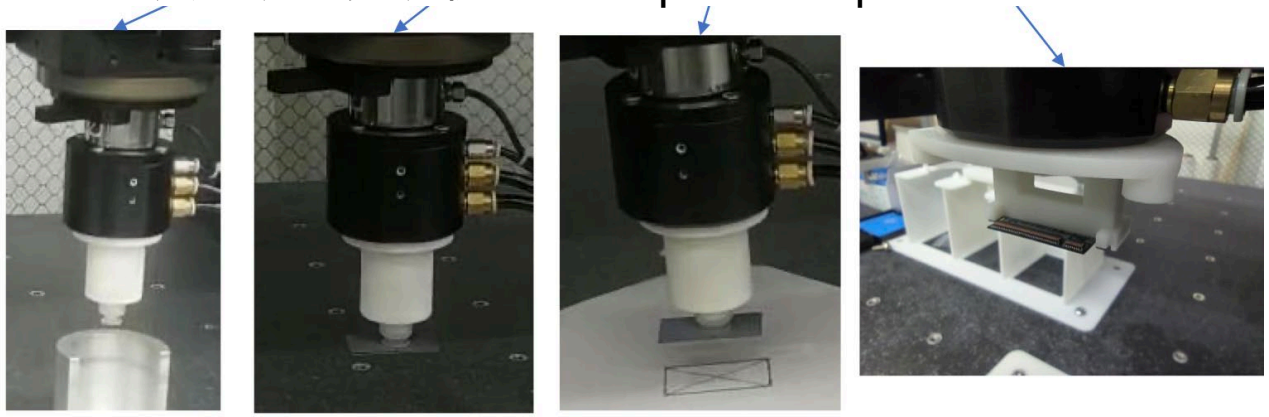
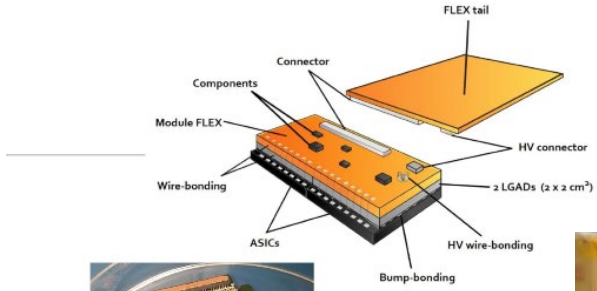
HGTD 探测器模块

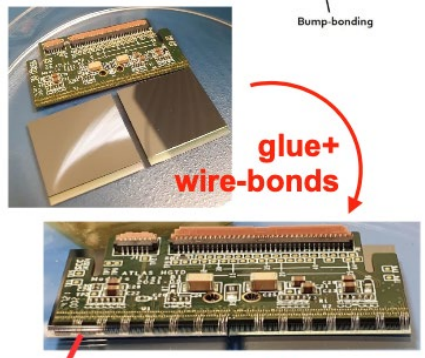
- HGTD项目总共需要8032个探测器模块
- 6个模块组装生产中心
  - 高能所，科大，德国，法国，西班牙，摩洛哥
  - 高能所是最大的生产中心，组装34%的模块
  - 中科大承担11%的模块组装
- 高能所与国内公司研制国产自动组装系统
  - 有高分辨图像系统，做芯片图像识别
  - 自动芯片组装、点胶
  - 位置组装精度达到微米级

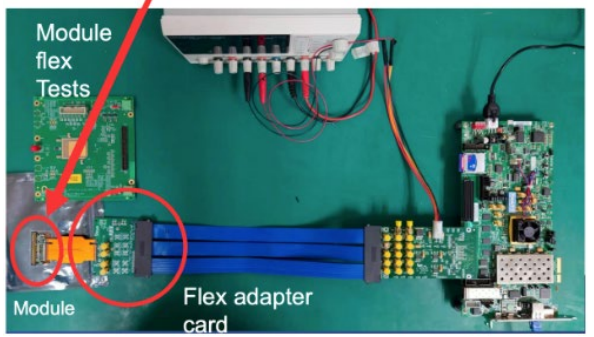
夹具工装和安装机器　　pick-and-place machine



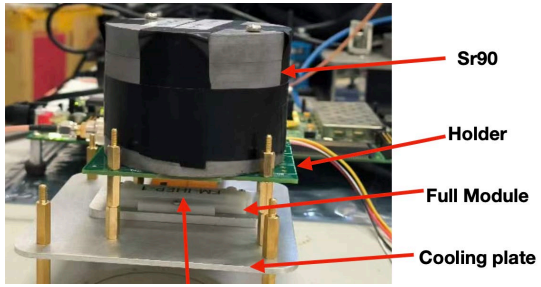
Picking tool　Picking dummy sensor　Placing dummy sensor　Picking flex

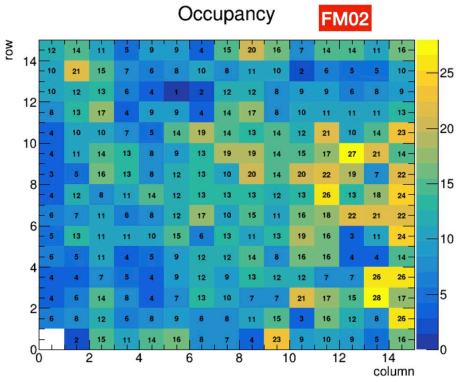






Sr-90 放射源测试





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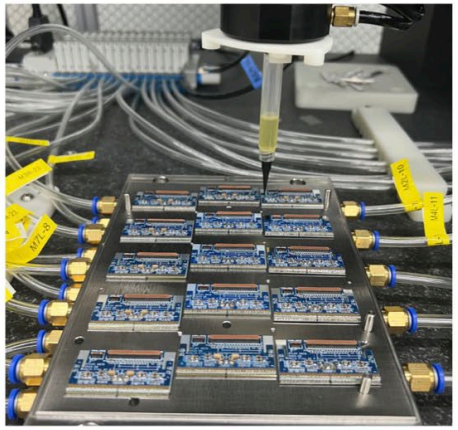
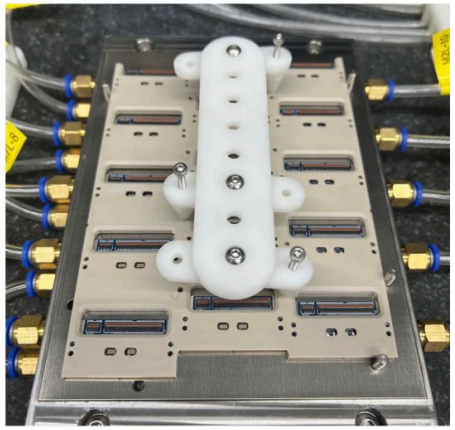
HGTD 探测器单元

- 高能所为HDTD制造出第一个 ALTIROC3 + LGAD 探测器单元（Detector Unit）
  - Use Gantry system to position all **15 modules** and glue dispending
  - Delivered to CERN, and passed reception tests

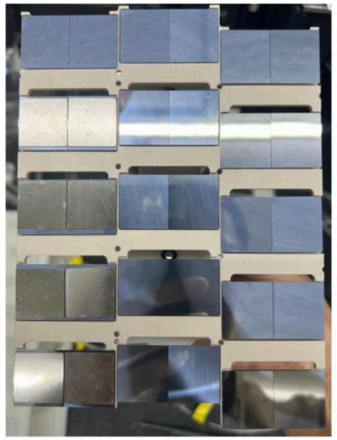
Dispensing with GluingTool



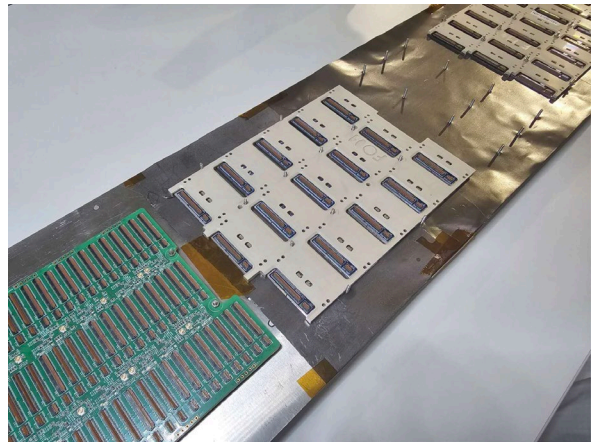
Put the support unit



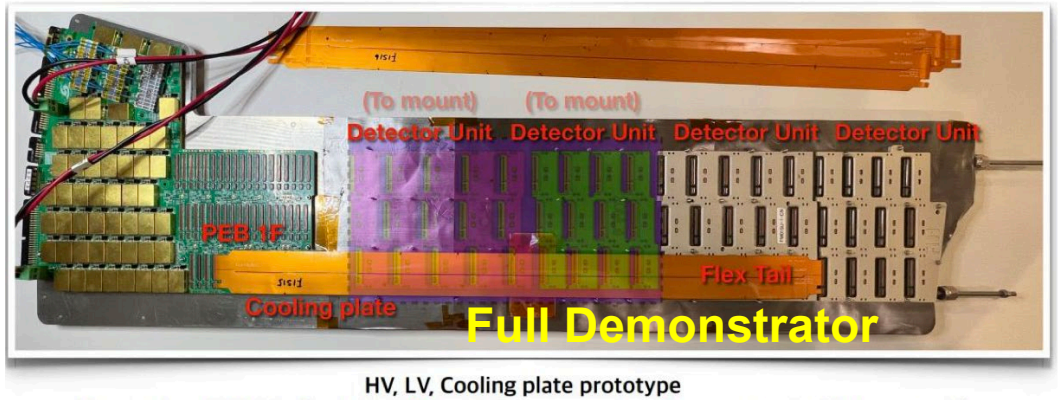
Backside view after removal



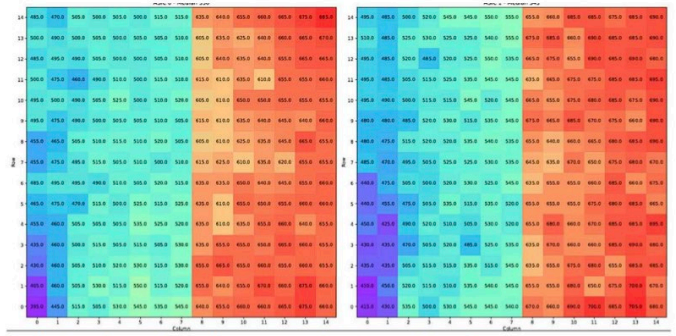
Detector unit shipped to CERN



- 首次在系统级演示探测器单元操作与运行 （外围电子学板PEB + 3*DU）



HV, LV, Cooling plate prototype
Electronics : PEB 1F + flex tails + 54 modules mounted on 4 support units (detector unit)



Module threshold scan obtained in demonstrator test

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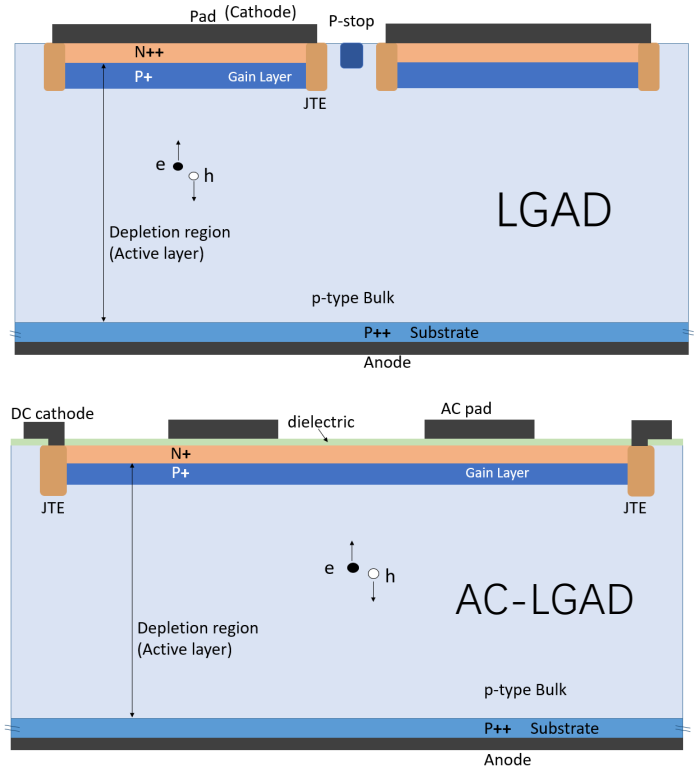
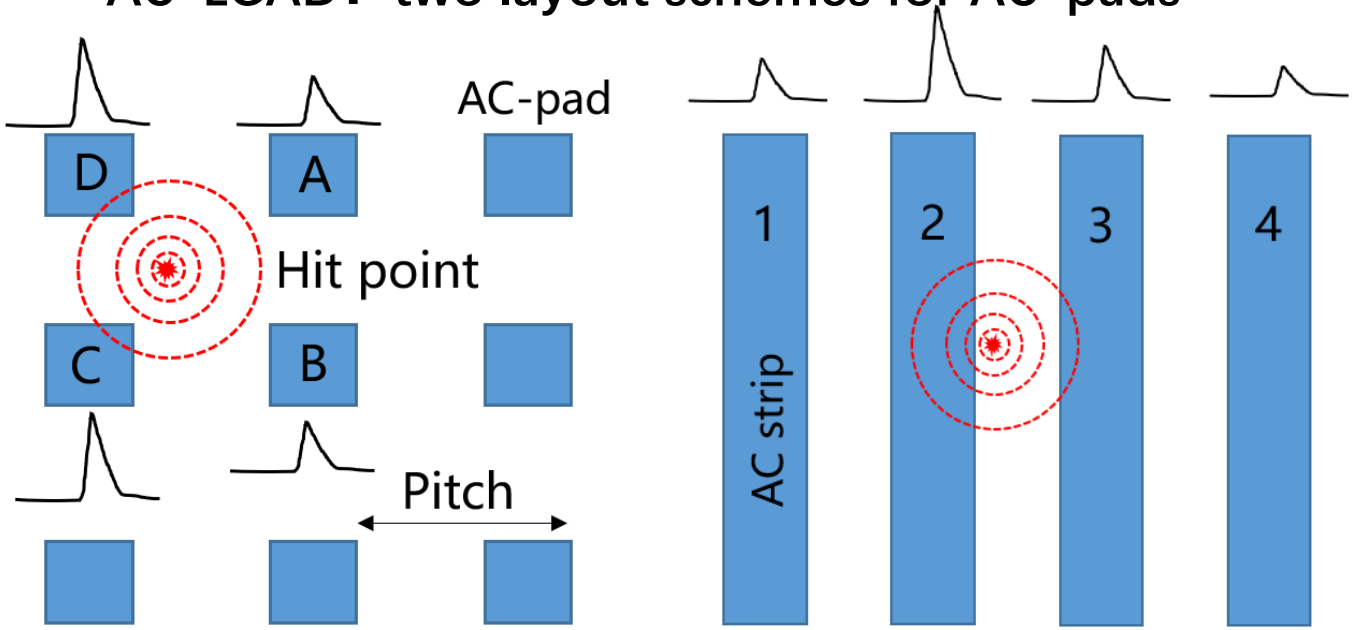
2. LGAD for Future Collider AC-LGAD 简介

LGAD vs. AC-LGAD



AC-LGAD：two layout schemes for AC-pads



- LGAD：The read-out electronics is connected to n++ layer
  - Dead zone ： JTE、P-stop
- AC-LGAD：Metal AC-pads separated from the n+ layer by a thin dielectric (Si_3N_4, SiO_2)
  - No dead zone (100 % fill factor)
  - Time resolution ~30 ps，spatial resolution ~10 μm

Pixels AC-LGAD：
- Position information：1 layer (x,y)
- Bump bonding

Strips AC-LGAD：
- Lower readout density，no bump bonding
- Position information：2 layers for (x,y)

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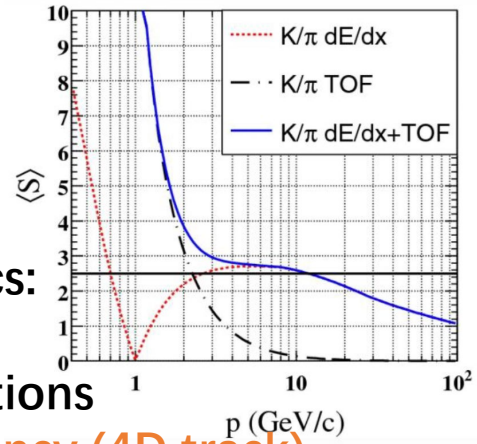
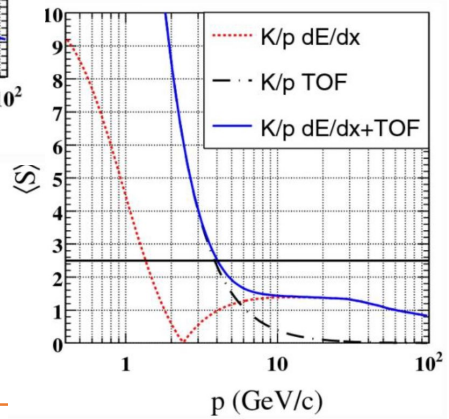
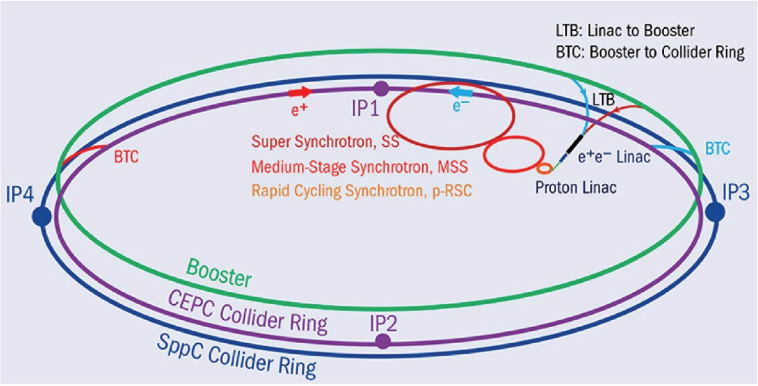
AC-LGAD研发背景

- CEPC will produce 10^{12} Z boson at Z pole: Rich flavor physics
- Particle separation problems of Gas detector (dE/dx) for flavor physics:
  - 0.5-2 GeV for K/pi separation, >1.5 GeV for K/p separation
- CEPC International Advisory Committee: one of the key recommendations
  Precision timing detector should be determined as a matter of urgency (4D track)
- Timing detector is complementary to gas detector: improves the separation ability
  0 - 4 GeV for K/pi separation, 0 – 8 GeV for K/p separation



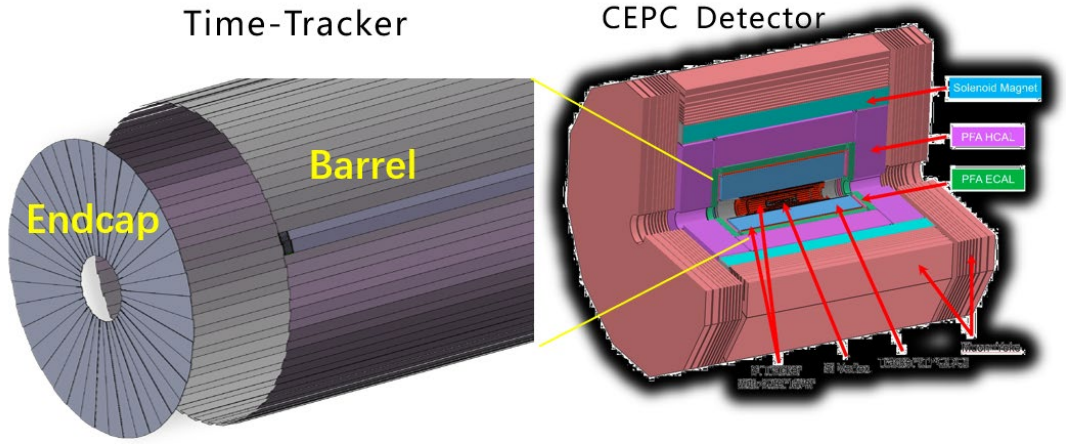


电子对撞机实验

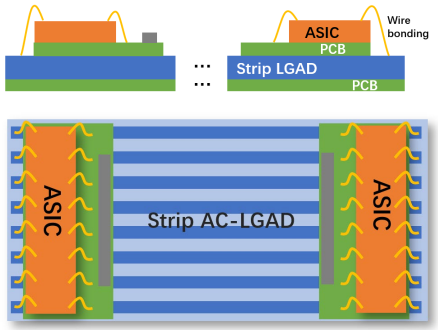


CEPC circumference 100 Km

时间-径迹探测器设计



探测器模块设计



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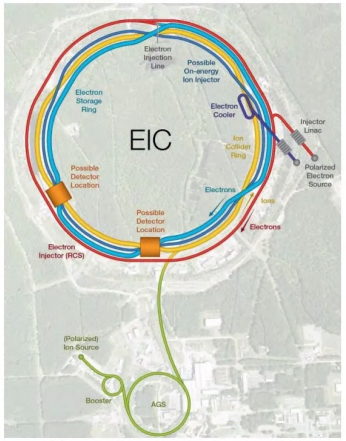
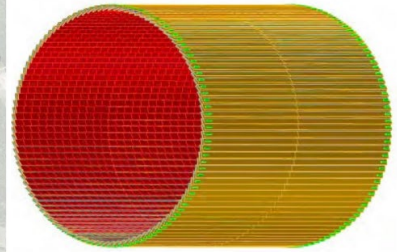
AC-LGAD研发背景

Electron-Ion Collider (EIC)：Timing-tracker

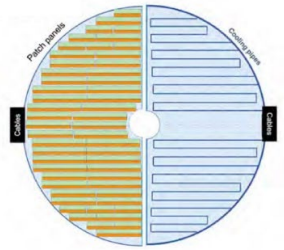


Barrel AC-LGAD detector



10.9 m^2

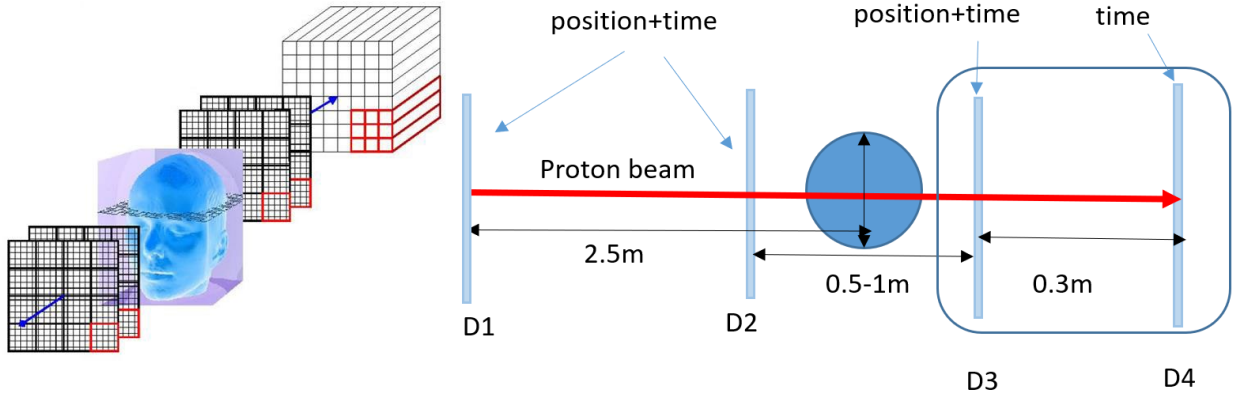
Hadron endcap AC-LGAD detector



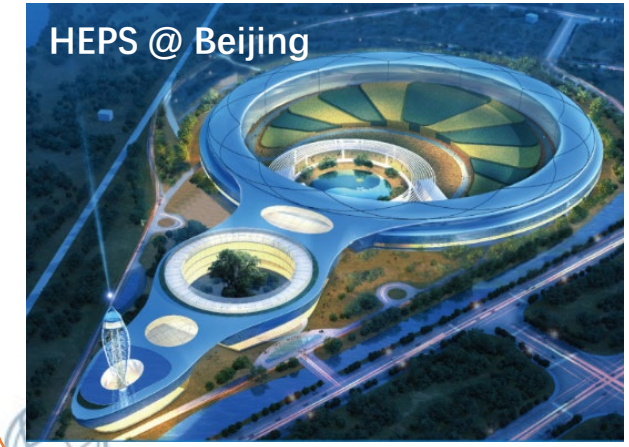
2.22 m^2

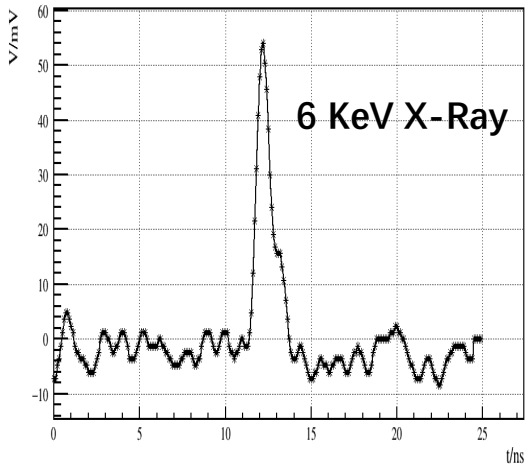
Nuclear Medicine Instruments:

Such as proton therapy and proton CT



X-ray detectors @ advanced photon sources





other applications

- Beam Telescope for Beam Test Platform
- LiDAR: Positioning and Navigation
- Track and time detectors in other particle physics and nuclear physics experiments
- …

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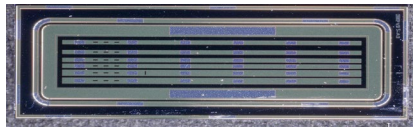
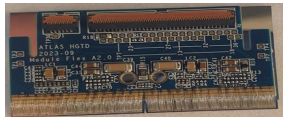
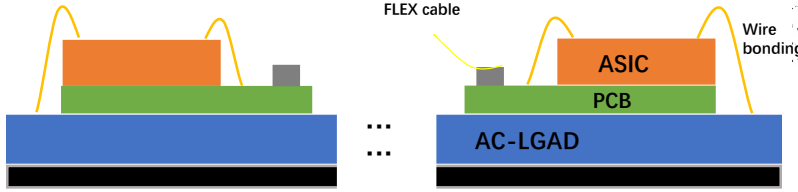
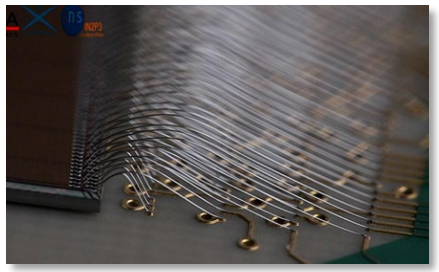
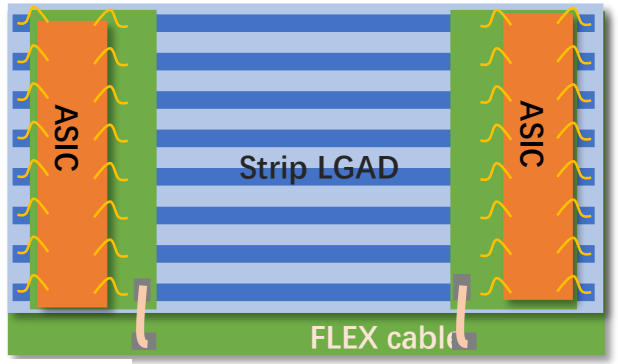
Time-tracker 桶部初步设计


+


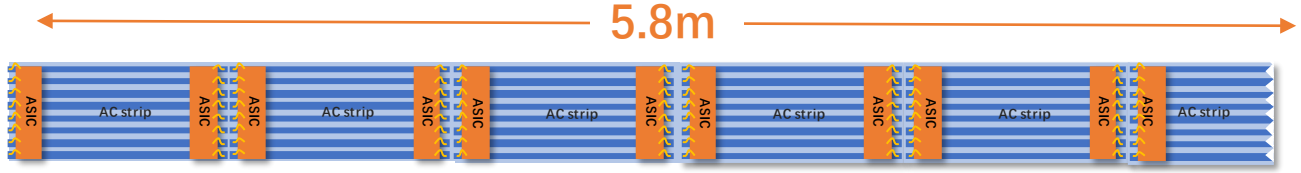






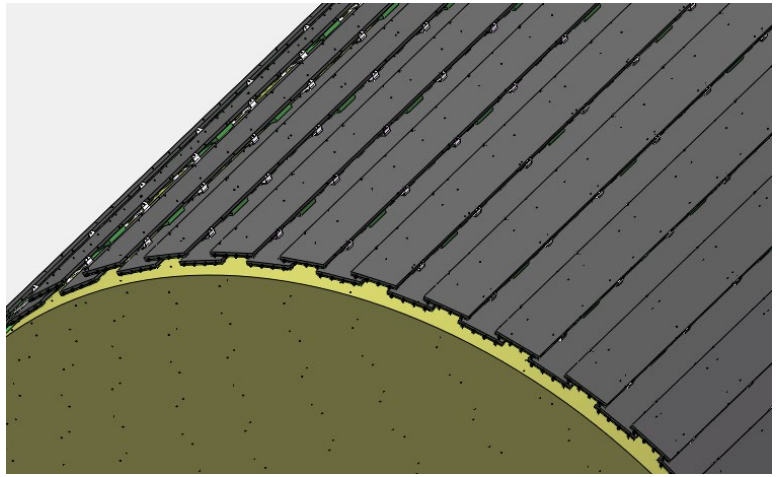
Strip AC-LGAD + ASIC：

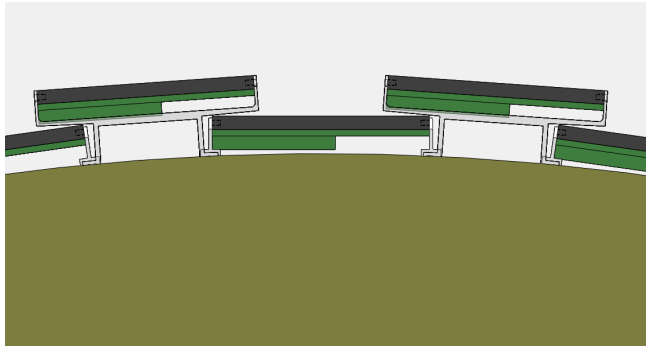
- TOT->amplitude/charge sharing->position
- TOA+TOT->timing (T-A correction)



Time-Tracker Barrel Parameters	
Area (m^2)	~ 70 m^2
Radius	1.8m
Length	5.8m
Granularity	70mm × 0.1mm
Channel number	~ 1×10^7 channels
MIP Time resolution	~50 ps
Spatial resolution	~ 10 μm (R-Φ) ~ 1 mm (R-Z direction)

PRELIMINARY





Preliminary Barrel Design

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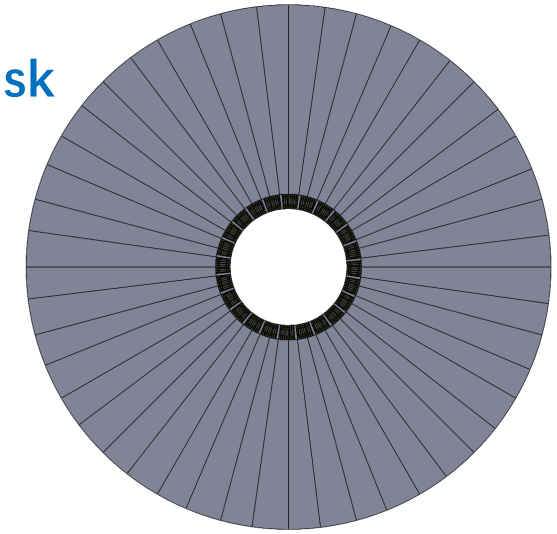
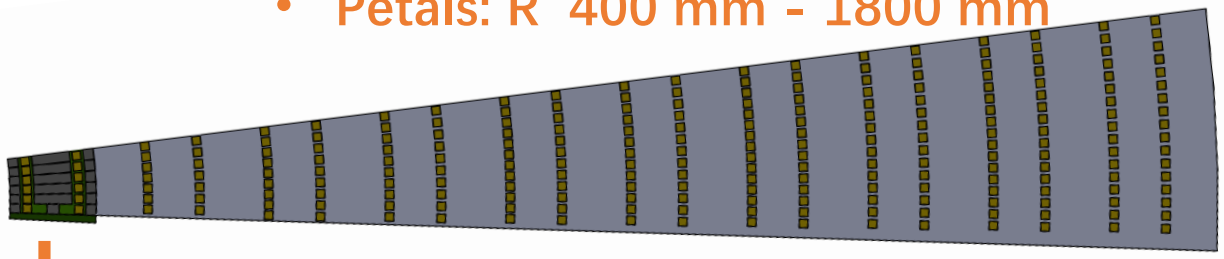
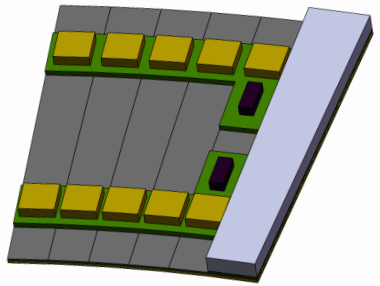
Time-tracker 桶部初步设计

- Double layers to reduce the dead area
  - 24 petals/layer
  - Petals: R 400 mm - 1800 mm

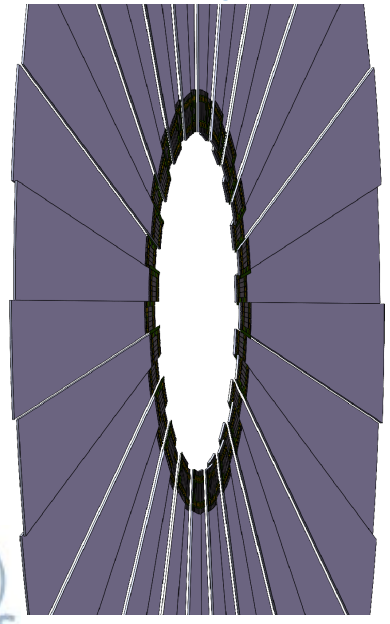
Disk





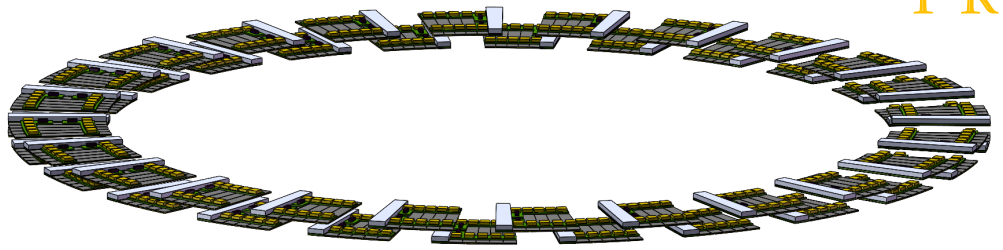


Double layer overlap



Time-Tracker	End-Cap Parameters
Area (m^2)	~ 9.7 m^2
Radius	0.4-1.8m
Granularity	140mm × 0.1mm
Channel number	~ 1×10^6 channels
MIP Time resolution	~50 ps
Spatial resolution	~ 10 μm (Φ) ~ 1 mm (R direction)

PRELIMINARY



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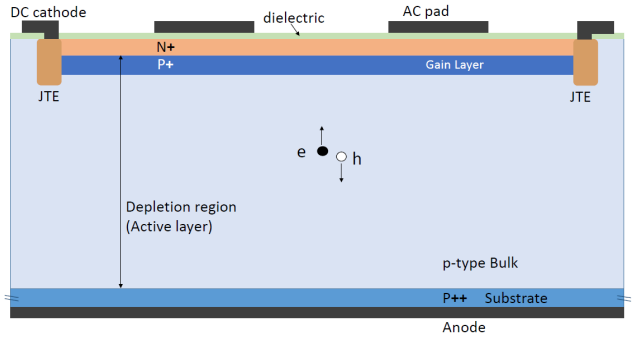
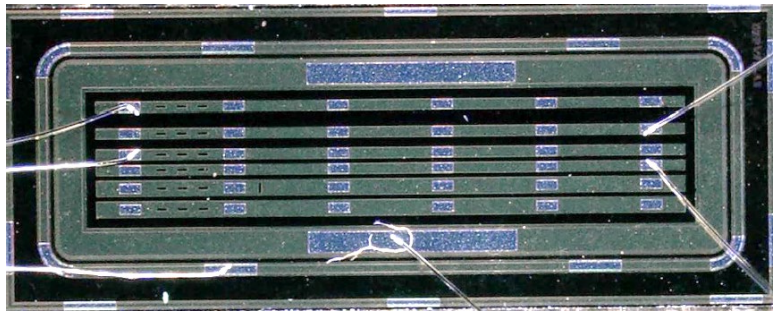
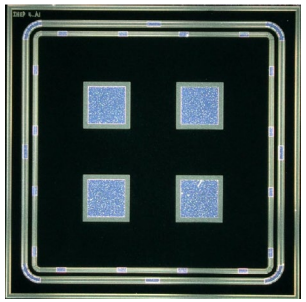
IHEP AC-LGAD 研制



AC-coupled LGAD



Strips AC-LGAD



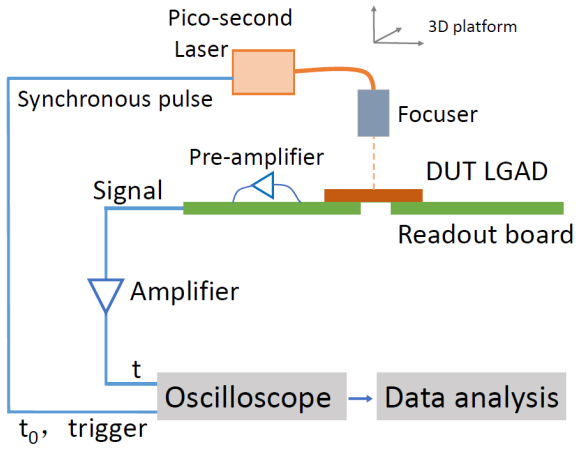
Pixels AC-LGAD

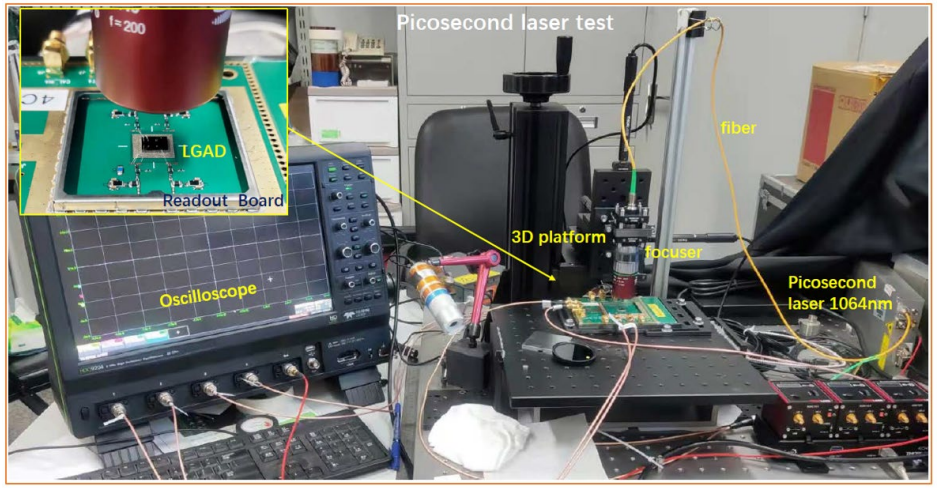
Pixels AC-LGAD：

- Pitch size 2000um
- pad size 1000um

Strips AC-LGAD：

- Strip length 5.6mm,
- Different Pitch size：
  - 150um、200um、250um





Picosecond laser scanning system

Picosecond laser scanning system

- Displacement accuracy 1 μm
- Automated scanning
- Picosecond laser 1064nm
- Spot size 2~5 μm

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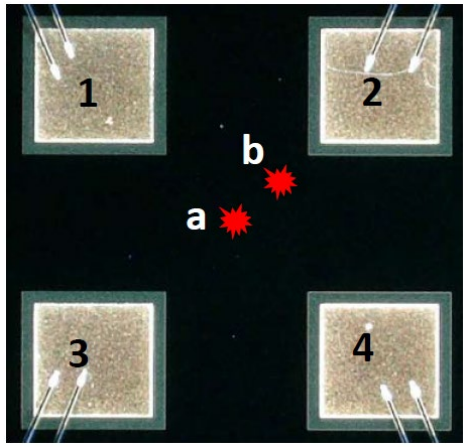
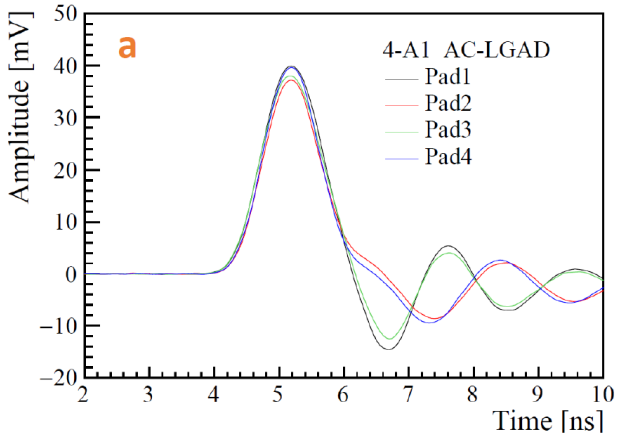
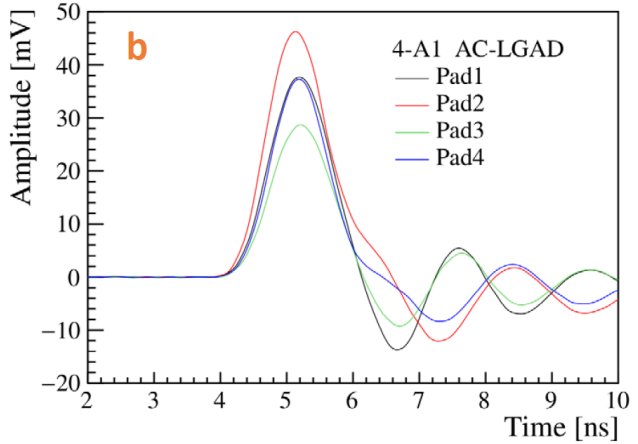
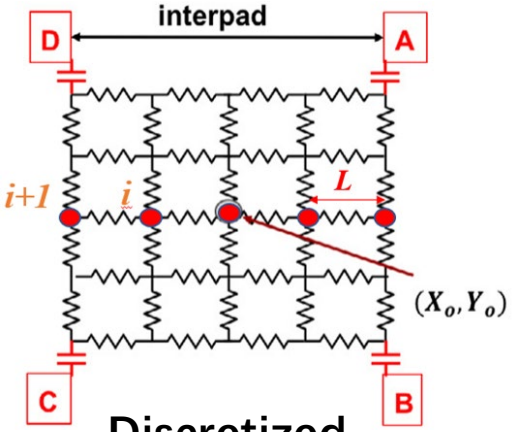
Performance of pixel-AC-LGAD



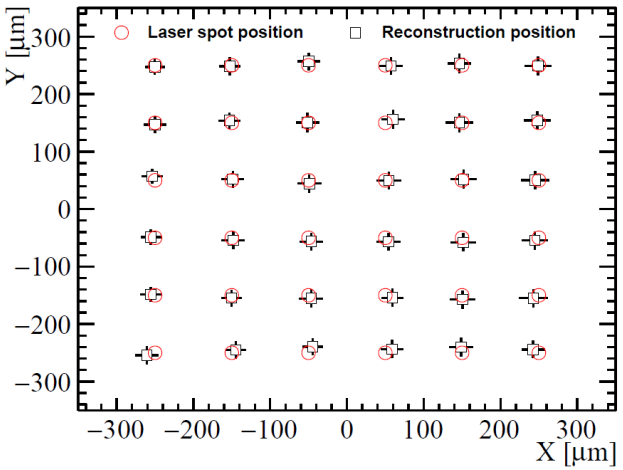




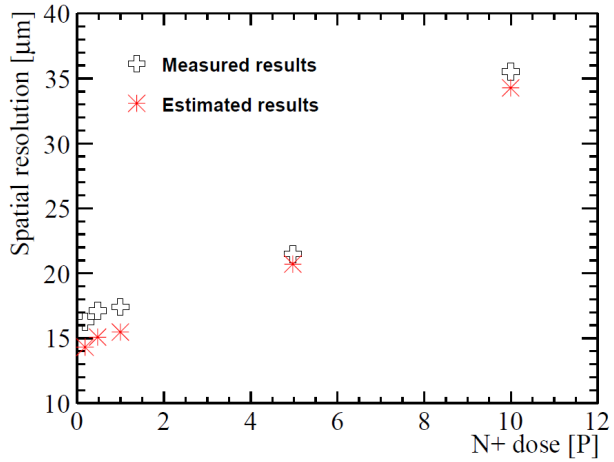
Signal Waveforms @ hit a and b



Discretized Positioning Circuit model (DPC)



Reconstructed 6x6 positions



Spatial resolution Vs. N+ dose

Spatial resolution：

- the sigma of the difference between the laser and the reconstructed position

$$\sigma_{spatial} = \sigma_{reconstruction-laser}$$

Lower N + dose has higher resistivity and larger attenuation factor, ->better spatial resolution

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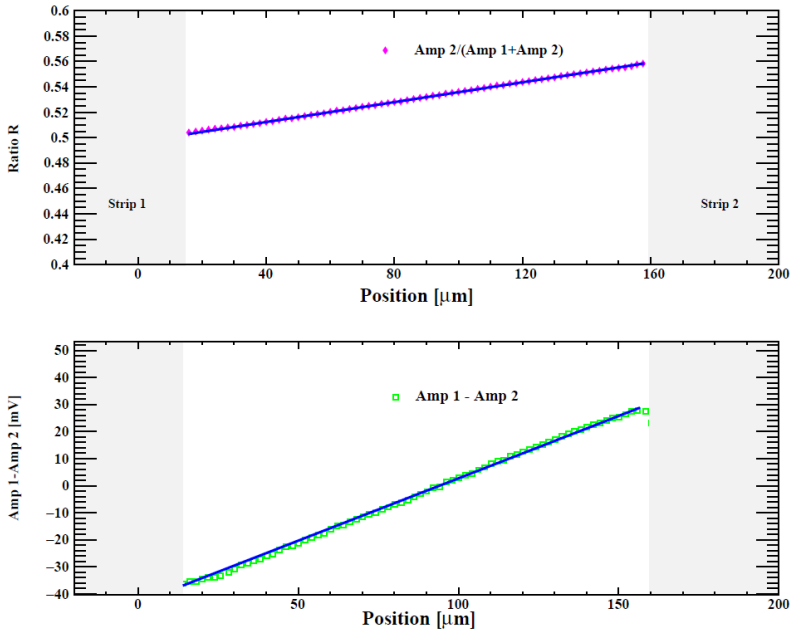
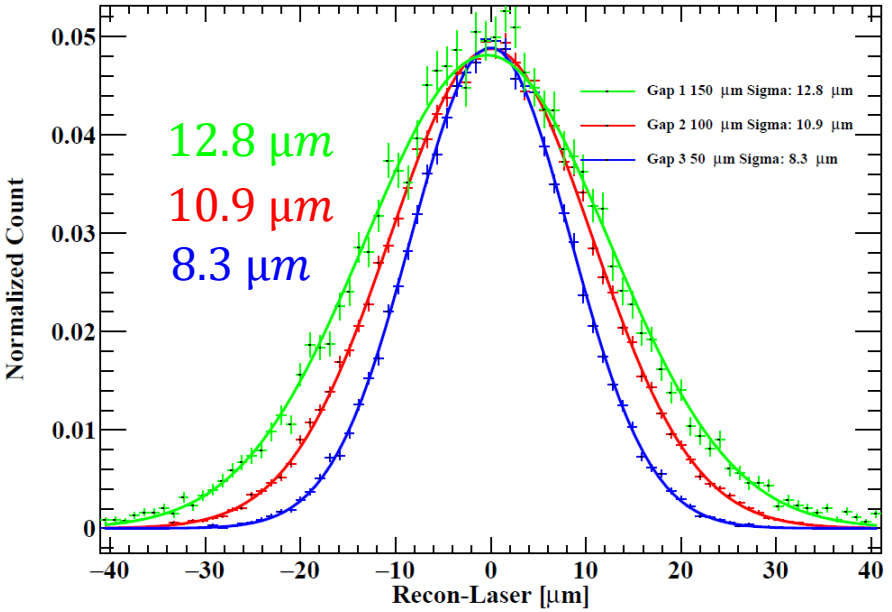
Performance of strip-AC-LGAD

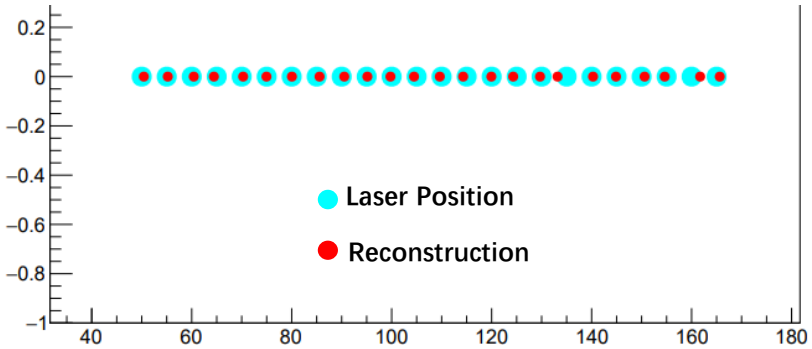


reconstructed position

$$R = \frac{Amp_2}{Amp_1 + Amp_2}$$

$$x = \frac{R - c}{k_R}$$





reconstructed positions

Position reconstruction:

- The fraction of the signal (*R*) changes linearly with the movement of the laser.
- Good consistency between the reconstruction position and the laser position
- The smaller the pitch size, the better the spatial resolution

Spatial resolution： $8.3\ \mu m$ @ $150\ \mu m$ pitch

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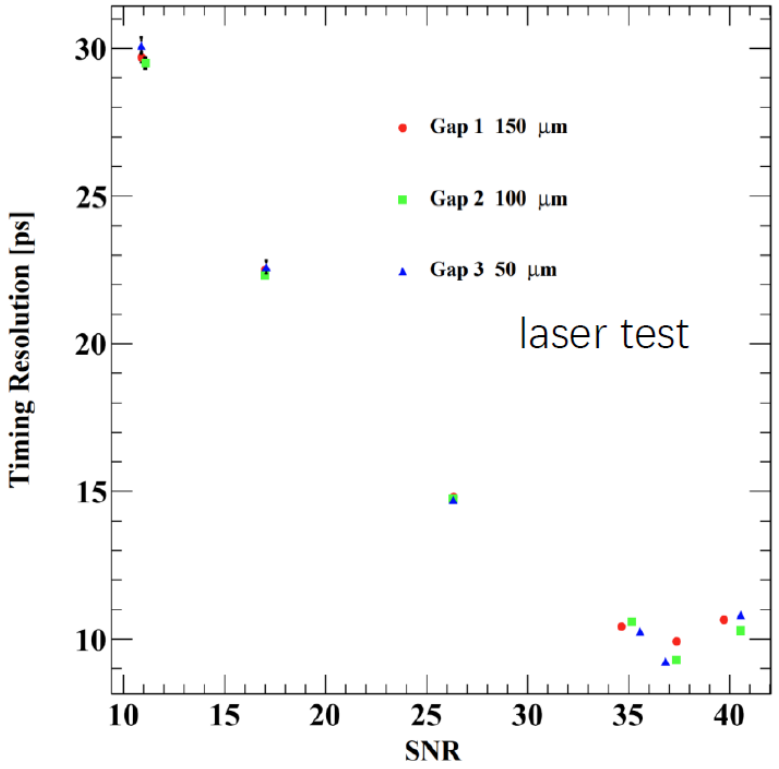
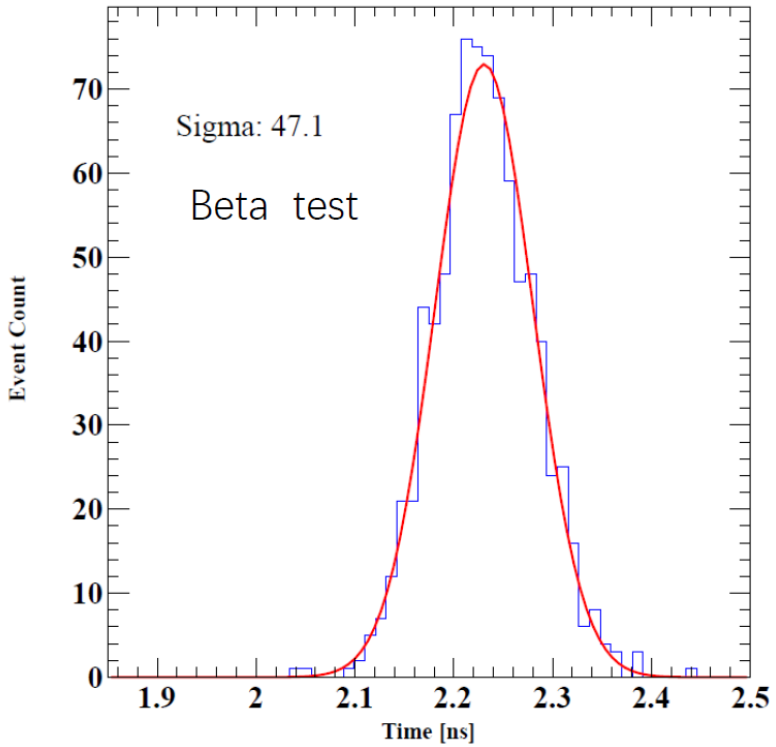
Performance of strip-AC-LGAD

Jitter tested by laser



Time resolution
tested by beta source



Timing resolution of Trigger

$$\Delta T = T_{trigger} - \frac{\Sigma_i a_i^2 T_i}{\Sigma_i a_i^2}$$

Timing resolution

Weighted timing resolution of three strip electrodes

Sigma Δt = 47.1 ps
Sigma AC-strip： 37.5 ps

- No significant change in timing resolution was observed among different pitches
- Timing resolution improves as increasing in SNR, same trend as in spatial resolution
- **Timing resolution 37.5 ps (Beta source test).**

$$\sigma_t^2 = \sigma_{TimeWalk}^2 + \sigma_{Landau}^2 + \sigma_{Jitter}^2$$

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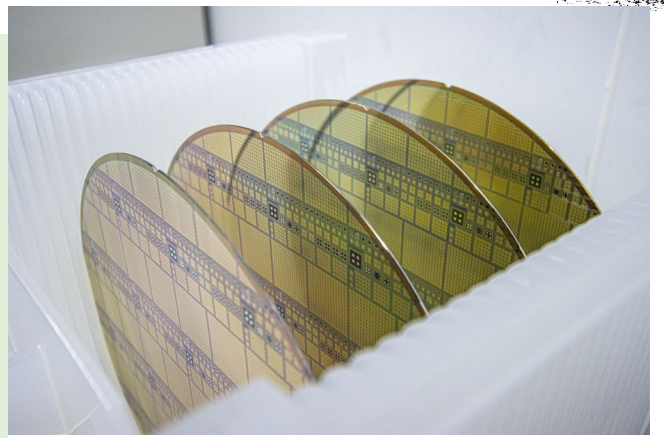
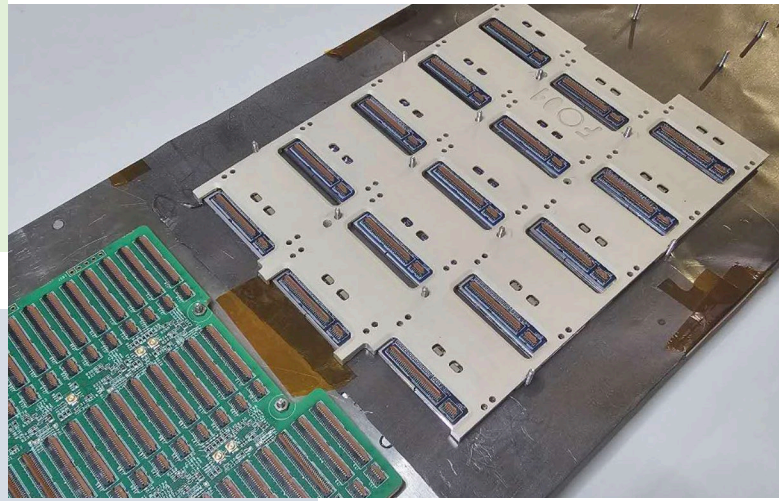
总结

中国组在ATLAS HGTD 项目中占主导地位

- 高能所、科大自主研制国产超快 LGAD 探测器，获得重大进展
  - 高能所赢得欧洲核子中心（CERN）国际招标采购的订单
  - 中国组负责全部的LGAD器件生产
    - 高能所-微电子所： 90%（66% CERN采购+ 24%实物贡献）
    - 中科大-微电子所：10% 实物贡献
  - 象征着国产硅传感器国际地位显著提升
- 探测器模块：高能所、科大将组装～4000个模块，占项目45%
- 外围电路：高能所、南大主导了外围电路板的设计与研制工作
- 2024年7月开始LGAD器件的量产





AC-LGAD： 新型的4D探测器（时间+径迹）：Pixel, Strip

- 基于strip AC-LGAD 的时间径迹探测器是CEPC的基准方案
- 目前高能所研制的strip AC-LGAD 空间分辨率约 8 μm，时间分辨率37ps
- AC-LGAD技术也被美国EIC实验选择用于时间-径迹探测器的建造
- IHEP AC-LGAD 研究规划：工艺优化、更长 strip 、先进重建算法、集成前放…

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谢谢